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IMPACT OF EDGE-BARRIER PINNING IN SUPERCONDUCTING THIN FILMS (POSTPRINT)

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14. ABSTRACT
It has been suggested that edge-barrier pinning might cause the critical current density (J_c) in bridged superconducting films to increase. Subsequent work indicated that this edge-barrier effect does not impact bridges larger than 1μm. However, we provide a theoretical assessment with supporting experimental data suggesting edge-barrier pinning can significantly enhance J_c for bridges of a few microns or even tens of microns thus skewing any comparisons among institutions. As such, when reporting flux pinning and superconductor processing improvements for J_c comparisons, the width of the sample has to be taken into consideration as is currently done with film thickness.

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Impact of edge-barrier pinning in superconducting thin films

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It has been suggested that edge-barrier pinning might cause the critical current density (J_c) in bridged superconducting films to increase. Subsequent work indicated that this edge-barrier effect does not impact bridges larger than 1 μm. However, we provide a theoretical assessment with supporting experimental data suggesting edge-barrier pinning can significantly enhance J_c for bridges of a few microns or even tens of microns thus skewing any comparisons among institutions. As such, when reporting flux pinning and superconductor processing improvements for J_c comparisons, the width of the sample has to be taken into consideration as is currently done with film thickness. [doi:10.1063/1.3529945]

Enhancing the critical current density (J_c) of a superconducting film has been a major effort in high temperature superconductors (HTS). Recent efforts have been focused on raising the J_c of type-II HTS thin films via the introduction of particulate and columnar flux pinning centers, especially in $YBa_2Cu_3O_{7-x}$ (YBCO).[1–8] To evaluate the effectiveness of these pinning centers made at the various institutions, the data are often compared with each other. However, the samples' geometric sizes can distort the comparisons, making it difficult to ascertain the relative improvement in a straightforward manner. For example, it is well known that the J_c of these thin superconductor coatings will decline as the sample thickness increases.[9] Most researchers conceptually account for this sample-thickness dependence when comparing J_c values.

In order to measure the J_c, superconducting strips are often cut with narrow bridges (5–20 μm, for example) to allow for more accurate measurements. It is of interest that narrower bridges tend to yield higher J_c's. While this may initially be ascribed to sample inhomogeneity, vast improvements in uniformity of the sample do not seem to alter this trend. It has been previously reported that the HTS sample edge can effectively provide a barrier to magnetic flux delaying its penetration into the sample.[10–13] This is true even if the vortices in the interior of the thin film are completely unpinned as in the case of no bulk pinning in a sample. Thus, the geometrical edge barrier can have an impact on the overall pinning affecting the properties of YBCO thin films.

Based on experimental observations, one group suggested that the edge barrier's pinning effect does enhance the J_c in narrow bridges,[14] but a subsequent report concluded that this enhancement is negligible in widths greater than 1 μm.[15] The data in that report, however, were limited to just three samples. In light of this, the bridge width used to measure the J_c of a given HTS sample is often not considered when data are reported. The work performed here provides both a theoretical basis and a broader experimental data set that demonstrates this edge-barrier enhancement is important at bridge widths up to tens of microns. This can explain the high J_c values consistently found in these narrowly bridged samples.

We consider a theoretical model by Elistratov *et al.*[16] and extended by Benkraouda and Clem[13] to calculate the relative pinning of the edge barrier. For this research, consider a superconducting strip centered on the z axis with width W ($|x| < W/2$) and thickness d, where W is much larger than the two dimensional screening length, $\Lambda = 2\lambda^2/d$. Here $\lambda = \lambda(0)/\sqrt{1-(77K/T_c)^4}$ is the London penetration depth at temperature of 77 K. In our case the thickness d is somewhat larger than the London penetration depth λ, see Refs. 13 and 17. The strip carries a total current I in the z direction. Then for a strip containing no magnetic flux and with no applied magnetic field, the sheet current density $K(x)$ in the z direction is simply determined by the Meissner-state current density generated by the applied current I, $K(x) = I/\pi\sqrt{(W/2)^2 - x^2}$.

With no applied field ($H_a = 0$) we can account for the edge barrier with the equation $I_{s0} \approx \pi K_s \sqrt{W\Lambda}$ where I_{s0} is the geometrical-barrier critical current in absence of bulk pinning and K_s is the sheet current density at which vortices nucleate and enter the superconductor and the barrier is overcome. For an ideal edge $K_s = j_{GL} d$, where j_{GL} is the Ginzburg–Landau depairing current density. Since an edge is inevitably not perfect, this provides a maximum pinning force. However, j_{GL} can be scaled to experimental data to account for the nonideal edge.

Using the temperature dependent depairing current density[18–20]

$$j_{GL}(T) = \Phi_0/[3^{3/2}\pi\mu_0\lambda(T)^2\xi(T)] \quad (1)$$

the equations from Elistratov *et al.* can be solved in terms of width and temperature. Incorporating a dimensionless parameter $p = I_p/I_{s0}$, we can characterize the critical current I_c for when $p < (\pi/2)$, the strip is vortex free and the edge barrier dominates ($I_c = I_{s0}$), and when $p > (\pi/2)$, the critical

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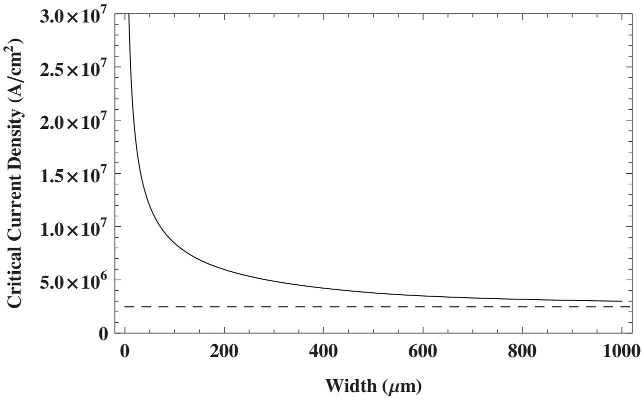

FIG. 1. The dotted line represents J_p and the solid curve represents the calculated J_c assuming a perfect edge. This curve represents the maximum J_c enhancement the edge barrier can have on a superconducting strip. Both curves are plotted for $T=77$ K. Note that as the bridge width increases, the true J_c asymptotically approaches the value of J_p. For this plot we used the empirically derived equation $J_p(T)=c(1-t^a)^b$, $c=7\times10^7$, $a=9/10$, $b=7/4$, $t=T/T_c=77/92$.

current is dependent on the combined edge barrier and bulk pinning effects. The critical current is found by simultaneously solving the equations[16]

$$1 = (1-b)\sqrt{\frac{1+a}{1-a}}\Pi\left(\frac{b-a}{1-a},q\right)p \tag{2}$$

and

$$1 = (1+a)\sqrt{\frac{1-b}{1+b}}\Pi\left(\frac{b-a}{1+b},q\right)p \tag{3}$$

for a and b where $q=W(b-a)/(W/2-a)(W/2+b)$ and Π is the complete elliptic integral of the third kind. The critical current of the strip is then

$$I_c(p) = \left(-\frac{a+b}{2\sqrt{(1-a)(1-b)}} + \frac{p}{2}\sqrt{\frac{1+b}{1-a}}\{(1-a)E(q) + (1+a)K(q)\}\right)\times I_{s0}, \tag{4}$$

where a and b are the results of simultaneously solving Eqs. (2) and (3). Here $E(q)$ and $K(q)$ represent the complete elliptic integral of the second and first kind, respectively.

We can plot J_c as a function of width and compare it with the critical current density (J_p) resulting only from bulk pinning, i.e., ignoring edge-barrier effects, to determine how much the edge barrier can enhance the critical current. From Fig. 1, we can easily see that the sample width can play a strong role in enhancing the critical current, even in bridges as large as 200 μm assuming a perfect edge. It should also be noted that for a nonzero applied magnetic field, not shown here, the edge-barrier effect rapidly diminishes. This modeling suggests two possible experimental approaches, among several potential, to demonstrate the effect. One is to repeatedly narrow a given bridged sample to smaller widths measuring the J_c after each size; two, plot $J_c(T)$ curves for a couple different bridge sizes on samples that have a similar J_c prior to bridging. Each approach can lead to different experimental difficulties, as discussed later, but was used to collect data in this work demonstrating the effect.

The details of the deposition conditions and processing are given elsewhere.[1,21] In short, strips of YBCO films were produced via pulsed laser deposition on $SrTiO_3$ single crystal substrates and annealed in a partial oxygen atmosphere. Bridges were patterned and etched using standard photolithography techniques. Critical current and transport J_c measurements were made at 500 μm bridge width as a baseline value. The samples were then etched to 200, 100, and 50 μm, respectively, with measurements made after each cut. The widths and film thickness of the microbridges made by photolithography were measured typically 8–10 times in different locations with a calibrated P15 KLA-Tencor profilometer, www.kla-tencor.com, to obtain a representative cross-section area with standard error less than 1%. By etching the same sample repeatedly differences of J_c due to sample variance are avoided and provide a direct comparison. However, the repeated etching and measurement can and did result in sample failure, but when this occurred it would only cause the sample's J_c to degrade; it would not increase the value. This explains why more data exist at the larger bridge sizes for the different samples.

Due to photolithographic equipment limitations, bridge sizes below 50 μm were patterned using a focused ion beam. Samples were cut using a constant aspect ratio method, where the bridge length to width ratio is 4. The same width progression as previous samples was attempted but this resulted in very high failure rates due to ion implantation and the resulting YBCO degradation. This high failure rate is similar to reports in the literature by other groups.[22–24] As such, only two usable data points were obtained having widths of 10 and 11 μm.

For the second approach, bridged samples were created from the same batch where the J_c of several "sister" samples could be verified for uniformity. Previous work demonstrated good uniformity of samples from the same deposition batch. Minor differences would and did exist in sample J_c but would be quantifiable in comparisons. Photolithography at other facilities (University of Kansas) allowed bridges to be made at 2, 5, and 15 μm.

To ensure proper measurement of the cross-section for an accurate determination of J_c, we followed the suggestion of Ref. 15 and measured the resistance of the bridge to derive its cross-sectional area. We also calculated the cross-sectional area based on measurement of the bridge directly. In the former case we assumed the same resistivity to determine the cross-sectional area and in the latter case we assumed accurate measurement of the bridges narrowest cross-sectional area. Only in the narrowest bridge widths did the two measurements vary in some noticeable fashion. Even so, the data led to the same conclusion.

Figure 2 shows the normalized J_c versus bridge width data collected for the first approach. Note that there is a gradual increase in J_c as the sample bridge width decreases. For the two samples that were bridged to a narrow bridge size of a few microns without damage, a significant increase is present in accordance with the theory. Using these initial experimental data we collected, the theoretical curve was fit to data and plotted in Fig. 2, represented by the solid black curve. The curve fit was done by taking $K_s=\sigma j_{\mathrm{GL}}d$ instead of taking $K_s=j_{\mathrm{GL}}d$, where j_{GL} is calculated using Eq. (1). In this case the value of σ is roughly 20%. This is reasonable in that for the smallest samples that have previously been reported were able to achieve close to 30% of the depairing current

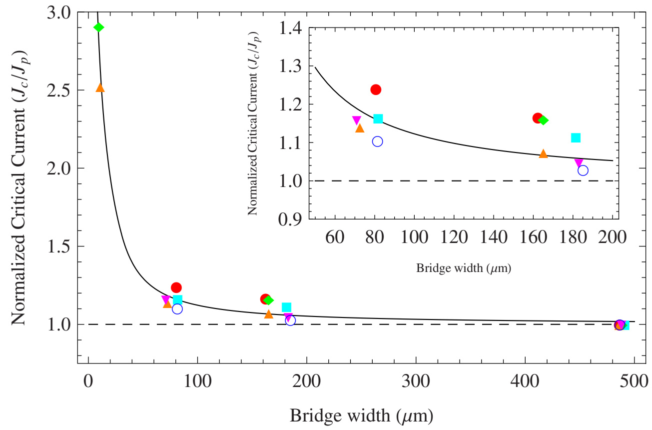

FIG. 2. (Color online) The black line represents the scaled J_c curve normalized by J_p. Markers of the same color and shape correspond to a single sample at different bridge widths. Data points are normalized with respect to the J_c of the 500 μm bridge, which were all in the range of 3–4.5 MA/cm^2. All measurements were done at 77.2 K and sample thickness is $\frac{1}{4}$ μm for each sample. In the above plot the Ginzburg–Landau depairing current density has been scaled by 0.2 for the theoretical curve. The inset is a simple magnification of the widths from 50 to 200 μm emphasizing that there is a significant J_c enhancement within this range.

density.[24] Although the edge is nonideal as expected and the J_c improvement is less than maximum, it clearly plays a strong role in bridges of tens of microns which are often used by various research institutions.

For the second approach two samples with a similar J_c were bridged to 2 and 5 μm and measured as a function of temperature. According to the scaled theoretical curve given in Fig. 2, a 58% enhancement should be seen in the 2 μm bridge over that of the 5 μm bridge. The experimental results show an overall 61% enhancement thus supporting the exponential increase in J_c for small bridge widths. A plot of these two curves is provided in Fig. 3. All sister samples from the same deposition were within 0.5 MA/cm^2 of each other at 77 K and cannot account for the difference. Note that this relative enhancement is over that of the 5 μm bridge which would in turn be an enhancement over bridges of 500 μm. The key point is that both approaches used to verify the edge-barrier effect suggests the importance of the edge barrier in narrow bridge sizes.

The initial experimental data clearly suggest the presence of the edge barrier and is not contradicted by either

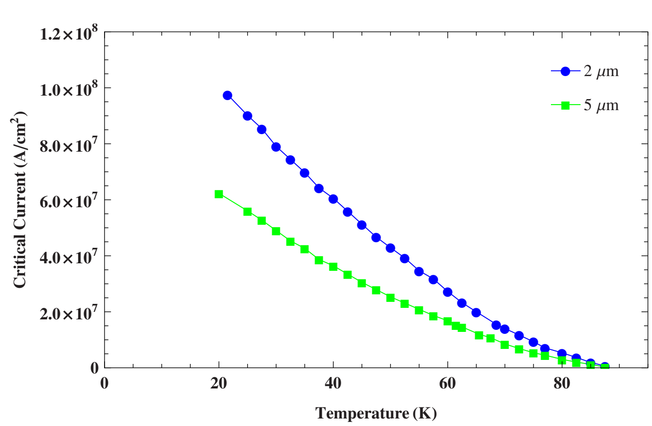

FIG. 3. (Color online) Measured transport $J_c(T)$ curves for bridges of 5 and 2 μm.

approach used. This concept is clearly critical to understanding the true value of the pinning enhancement for institutional comparisons, especially since often the bridge size used to determine the J_c is not reported in publications. Narrow bridges of a few microns or even tens of microns can greatly increase the critical current density (over 200% under certain conditions) thus skewing any results for comparison. As such the bridge width must be reported in addition to the film thickness. The edge-barrier effect is more relevant to self-field enhancement since it is negligible for most in-field measurements.

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